Development of Finite Element Models for Evaluation of Safety Footwear and Metatarsal Impact Protection

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I. INTRODUCTION

Previous studies have characterized metatarsal fracture risk under quasi-static loading and simulated workplace impact loading, indicating that fracture risk is more accurately determined by impact force than by deformation at the metatarsals [1-2]. However, current standardized testing methods for metatarsal guards specified by CSA Z195-14 and ASTM F2412-11 use modeling clay or wax as a surrogate for the human foot and measure the deformation of the clay or wax to assess metatarsal fracture following a controlled impact [3-4]. These test methods and metrics used in current industry standards conflict with the current literature surrounding metatarsal fracture risk and mechanisms; therefore, the development of a new approach to evaluate the efficacy of metatarsal guards for injury prevention is needed. The main objective of this work was to develop a computational tool based on detailed finite element models of safety footwear, metatarsal guards, and the human foot to evaluate effectiveness of current metatarsal protection and possible metatarsal injury through simulation of industry standard footwear test methods.

II. METHODS

A detailed finite element model of the human foot was obtained from the Global Human Body Models Consortium (GHBMC). An elastic-plastic material model with erosion by plastic strain was applied to the metatarsals and meshes were refined for the first through third metatarsals to avoid unrealistic stress concentrations on those most implicated in impact fractures [2][5-7]. Bulk soft tissue was modeled using the hyperelastic constitutive coefficients reported by Fontanella *et al*. [8]. The force-displacement response of this model during barefoot impact was compared to the available cadaver data under the same impact loading to verify a reasonable response in peak force and displacement during impact [2]. The foot model was scaled to the specified shoe size and to fit inside the boot model [3-4]. 3D models of men's size 9 work boot components (outsole, midsole, and upper) were generated from 3D scanning and existing geometry files. The impact response of the boot model was validated against experimental impact data from the empty boot. A model of a soft foam external metatarsal guard was also developed from a 3D laser scan. The upper, outsole, midsole, and metatarsal guard components were meshed with hexahedral elements at a target size of 4mm, 1mm, 1.5mm, and 1mm, respectively. The material models for the boot components were derived from experimental data and existing literature [9]. The metatarsal guard was modelled as sulfur-vulcanized rubber, a sample soft material [10].

Standard impact tests required by CSA Z195-14 or ASTM F2412-11 were modeled with a cylindrical impactor and a rigid floor plate. The assembled test configuration is shown in Figure 1. Test simulations were conducted for the bare foot and the empty boot, and further simulations were conducted to compare the boot and metatarsal responses with and without metatarsal guard protection. All simulations were performed in LS-Dyna SMP R9.0.1 and represent an impact energy of 33 J, which corresponds to approximately a 50% risk of metatarsal fracture at the 3 m/s impact velocity used in the standard test [2-4].

III. INITIAL FINDINGS

Sample stresses at the metatarsals at impact initiation, with stress values greater than 180 MPa indicating bone fracture, are shown in Figures 2 and 3 for unprotected and protected impacts, respectively. Corresponding sample stresses on the metatarsal guard are shown in Figure 4. The observed maximum von Mises stress values, which correspond most closely to the bone failure threshold criteria and the proposed fracture risk indicator,

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were 213MPa for the unprotected metatarsals (third metatarsal, fracture) and 11.2MPa for the protected metatarsals (first metatarsal, no fracture) [2]. Maximum von Mises stress in the metatarsal guard was 23.8MPa.

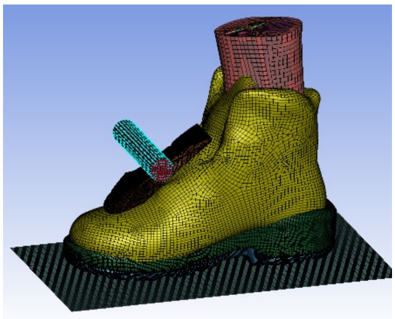

Figure 1: Boot model in simulated standard metatarsal protection test configuration

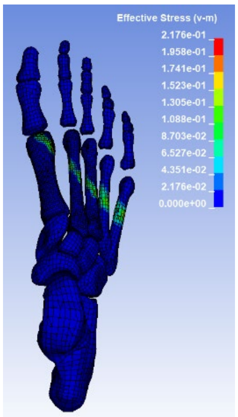

Figure 2: Unprotected von Mises metatarsal stress (GPa)

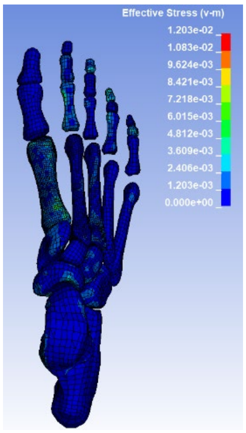

Figure 3: Protected von Mises metatarsal stress (GPa)

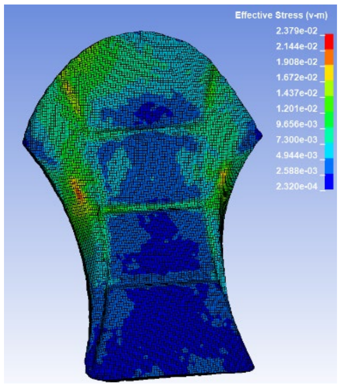

Figure 4: Sample metatarsal guard von Mises stress (GPa)

IV. DISCUSSION

The simulation conditions attempt to represent the standard test procedure as it is currently performed in industry, matching the specified drop tower conditions and allowing for adjustments to varied impact energies. The stress mappings clearly indicate that the metatarsal guard attenuates a large portion of the impact loading, resulting in about 96% reduction in stress and no bone fractures in the metatarsals at impact initiation when the foot is protected with a metatarsal guard. Peak stress values in the boot upper were similar for unprotected and protected impacts. The impact location specified by the standards, and thus implemented in these simulations, is more consistent with the location of the metatarsal heads than the mid-metatarsal region, affecting the observed fracture response and limiting understanding of the protection offered by the metatarsal guards. Various soft tissue material models are available in literature and the GHBMC model – other material models may result in different stresses reported at the metatarsals but should not significantly affect the trend observed for metatarsal protection. Additionally, the single metatarsal guard material for this study was chosen as an example material and does not represent the full range of materials for soft metatarsal guards or materials used for rigid metatarsal guards. Work is ongoing to model other materials and metatarsal guard types for impact loading and to evaluate the metatarsal guards at higher impact energies.

Despite efforts to eliminate mesh-dependency through element quality and appropriate element size, a full mesh convergence analysis for the soft metatarsal guard is still pending, limiting the current model. Results of a mesh convergence study for the upper component indicate that the 4mm mesh yields reasonably mesh-independent results (within 2.3%), although refinement at the impact surface is preferred for future work. This model is also limited by various anatomical simplifications present in the GHBMC model, errors introduced by laser scanning, and geometric simplifications required to achieve acceptable mesh quality. Metatarsal guards may be external or integrated intrinsically in the boot; the current scope of this work is limited to external guards.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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